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Fatigue strength of laser hardened 42CrMo4 steel considering effects of compressive residual stresses on short crack growth

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Abstract

The paper contains results of a study aimed at an experimental evaluation of fatigue resistance and initiation mechanisms of heat treated and laser hardened 42CrMo4 steel. Experiments were performed using quite small specimens of 8 x 8 mm cross section, under three point bend fatigue loading. Two different parameters of laser hardening were used, one of them resulted in considerable longitudinal residual stresses – surface speed of laser beam 4 mm/s. Results of fatigue tests of basic reference material, just heat treated, were characteristic by a surprisingly high scatter, particularly in the region near fatigue limit. Fractographical analyses indicated that this scatter was connected with presence of surface or subsurface defects, mostly inclusions, even quite large, which in some cases caused fatigue crack initiation. Compressive residual stresses after the laser treatment, dependent on laser treatment parameters, improved fatigue strength and reduced the scatter, likely due to short crack retardation in the compressive residuals stress field. Further analyses were carried out using Murakami method of evaluation of fatigue life of materials containing defects. The Murakami model of fatigue limit evaluation of specimens containing defects was just slightly conservative, when applied to specimens just conventionally heat treated, but quite strongly conservative particularly in case of laser surface hardening with high longitudinal compressive residual stresses. The results indirectly confirm significant beneficial effects of compressive stresses induced by laser hardening on fatigue resistance caused by retardation or arrest of short fatigue cracks emanating from microstructure defects.

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Keywords: Fatigue strength; 42CrMo4 steel; laser hardening; residual stresses; short cracks.

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1. Introduction

Laser surface hardening is an advanced surface treatment method of structural steels with a great potential for wide industrial applications. In order to gain a comprehensive knowledge about effects of laser hardening and its parameters on microstructure, hardness, surface and other properties, systematic investigations have to be performed. If the technology is to be applied to components repeatedly loaded in service like gear wheels, fatigue resistance of the treated material becomes an issue (e.g. [1]).

Recent results and knowledge published in the literature indicate that fatigue resistance can be either reduced or increased, even considerably, depending on basic material and numerous parameters including those of laser technology itself. Fatigue strength and limit can be increased even by several tens of percents [2]. Particularly residual stresses and their distribution in surface and subsurface layers play an important role [3]. Note that a significant, positive effect of laser hardening using previous generation of lasers in a combination with subsequent surface polishing on fatigue strength in a high cycle regime and fatigue limit was shown and described already several years ago [4].

This contribution contains results of a partial study of effect of laser hardening of relatively small specimens on fatigue resistance of 42CrMo4 steel.

2. Experimental programme

A low-alloy premium chromium – molybdenum 42CrMo4 steel suitable for both heat treatment and surface heat treatment was selected for the experimental programme. The material was obtained in two versions of chemical compositions being commonly used, namely 42CrMo4 and 42CrMoS4, the latter having a guaranteed range of sulphur content, between 0.020 and 0.040 % with ± 0.005 % tolerance in a final product, which is usually higher than the sulphur content in the 42CrMo4 version. Analyses of actual chemical composition carried out using an optical emission SPECTROMAXx stationary metal analyzer showed a slightly higher sulphur content in the 42CrMo4 steel than that in the 42CrMoS4 modification – Table 1. So, the sulphur content was very similar in both steels.

Table 1. Actual content of elements in weight % in the used steels

Element (weight %)	C	Si	Mn	P	S	Cr	Mo
42CrMo4	0.452	0.221	0.780	0.014	0.021	1.07	0.182
42CrMoS4	0.465	0.219	0.740	0.014	0.020	1.05	0.176

According to the delivery sheets, the steels were heat treated. Since actual strength and hardness corresponded to the declared values, the first stage of the laser treatment and fatigue tests was carried out using the material as received. Later metallographic analyses, however, showed that the microstructure was rather of bainitic than martensitic character and was not optimally homogeneous (Fig. 1). Therefore, before continuing the experimental programme, the material was heat treated again with the same target values of strength and homogenous microstructure of tempered martensite (Fig. 2).

The material purity, evaluated according to [5], was quite typical for technological steels, namely oxides grade D2 and sulphides grade A2 for both steels. Inclusions were mostly tiny but single quite large inclusions could be observed, too.

Small specimens of 8 x 8 mm cross section and length 120 mm dedicated for fatigue tests at three point bending were manufactured. Laser hardening was always applied to one surface of the specimens. Laser equipment LaserLine of the 3.5 kW power was used, focus length 200 mm, laser beam speed 3 mm/s. In addition, speed 4 mm/s was used for some specimens from the heat re-treated group – with the martensitic basic microstructure. Laser power was automatically controlled so that the surface temperature was 1200 ^{o}C in all cases. Since laser beam width was more than 23 mm, three specimens were always treated together. During the process, the specimens were either loosely laid on a massive steel supporting plate (the first group of specimens with bainitic basic microstructure) or fixed at their end by spot welding (the second group of specimens – heat re-treated, with martensitic microstructure). Fatigue tests were performed at load frequency 40 – 50 Hz with load asymmetry R = 0.1, test span 100 mm.

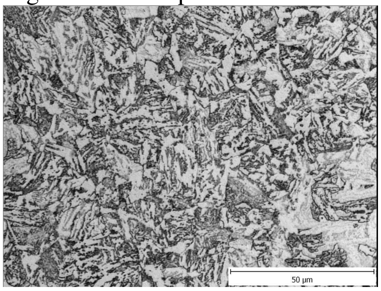

Fig. 1. Bainitic heat treated microstructure – as received state

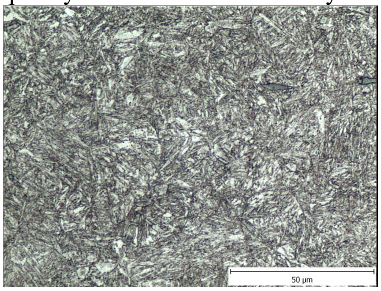

Fig. 2. Martensitic basic microstructure – after heat re-treatment

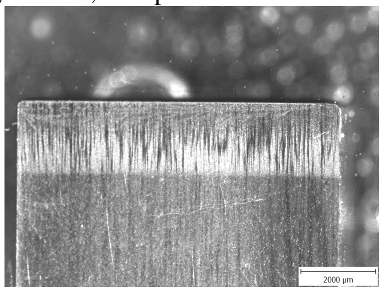

Fig. 3. Macroscopic view of laser treated area in specimen cross section

3. Experimental results and discussion

Hardness of the laser treated specimen surface was between 53 – 55 HRC and 42 – 46 HRC in case of the first and second group, respectively. The differences were likely affected by the different supporting methods during the treatment rather than by the slightly different basic microstructures – bainitc or martensitic, respectively. When the specimens were partially fixed to the supporting plate by spot welding, the heat transfer to the support was probably faster, which could partially affect the final hardness.

It looks from Fig. 3 that the thickness of the laser treated zone was almost 2 mm. However, the actual thickness evaluated from the 50 % drop of hardness was considerably lower, approximately 0.5 mm – Fig. 4. Note that microhardness values in Fig. 4 are characteristic with a very big scatter. Most of the experimental points are close to the average line, but there is a lot of single local areas with much higher values. Some differences between the curves of the 42CrMo4 and 42CrMoS4 steels, respectively, may be caused by different position of the specimen in relation to the laser beam. The specimen could be in the central or marginal position, as three specimens were treated together.

Results of fatigue tests are shown in Fig. 5. There are just several points of the first group of laser treated specimens – with the bainitic microstructure, because most of the tests were carried out with the second group of specimens. Besides laser treated specimens, two S-N curves of reference specimens of the 42CrMo4 and 42CrMoS4 steels, respectively, with just basic heat treatment, not laser hardened, were evaluated for a comparison. In addition, four laser treated specimens were tested after grinding a thin surface layer off. Laser treated surface was not namely smooth, it contained numerous microscopic pits of the diameter 20 – 50 µm, which could be potentially initiation points of fatigue cracks.

Results of fatigue tests are characteristic first of all by an unusually big scatter, including the material not laser treated. At stress range bellow 800 MPa, there are no breaks after 10^7 cycles on one hand and quite early breaks on

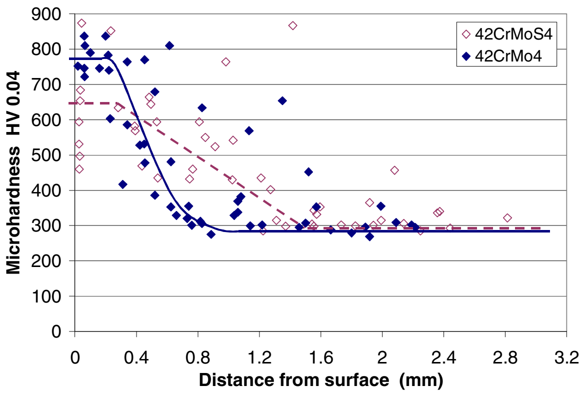

Fig. 4. Microhardness in and under laser treated surface – 1st group of specimens

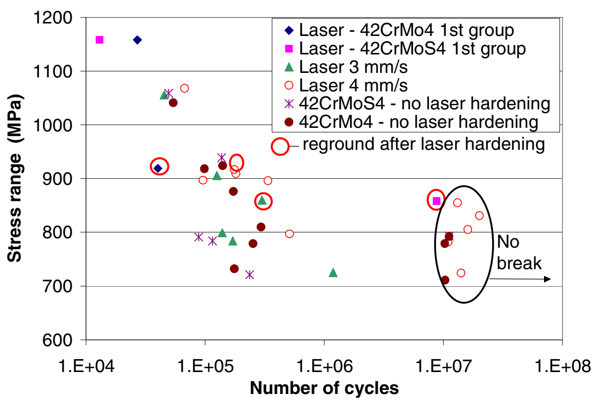

Fig. 5. Results of fatigue tests

the other hand. This concerns particularly the 42CrMoS4 steel. Unlike laser hardening with the surface beam speed 3 mm/s with neither positive nor negative effects, laser treatment with the speed 4 mm/s increased fatigue limit and reduced scatter. A possible explanation consists in quite significant compressive residual stresses induced by the treatment with 4 mm/s beam speed [6]. Note that in case of the 3 mm/s laser beam speed, residuals stresses were almost negligible.

Fractografical analysis of initiation mechanisms explained the scatter. It showed that in all cases, fatigue cracks were initiated on surface or even subsurface defects, mostly inclusions, of a very large size range. In several specimens, size of the initiation defects was exactly evaluated and Murakami model [7] was applied to calculate theoretical fatigue limit of such specimens. Actual relative fatigue life of these specimens was then compared with the calculated one. It was shown that calculations according to the Murakami model were slightly conservative for laser untreated specimens, by cca. 10 – 15 %, almost exact for laser treatment with 3 mm/s surface speed but considerably conservative for specimens treated with 4 mm/s beam speed – by more than 20 %. This result is very likely connected with the compressive residual stresses, which contribute to retardation or arrest of physically short fatigue cracks emanating from defects. A similar positive effect of residual stresses on short fatigue crack retardation was already described in the literature [8,9].

Note that no effect of regrinding after laser treatment on fatigue results can be observed from Fig. 5. This is not, however, a general conclusion, but just a confirmation that the effect of inclusions and other material defects on fatigue crack initiation in this specific case was stronger than microscopic surface pits resulted from laser treatment.

4. Conclusions

Results of the investigation of effects of surface laser hardening applied to heat treated 42CrMo4 steel and its 42CrMoS4 modification on fatigue resistance can be summarised as follows:

- Fatigue results were characteristic by an unusually big scatter, probably affected by fatigue crack initiation on inclusions and material defects of different size.
- Unlike laser treatment with surface beam speed 3 mm/s, which was neither positive nor negative, laser treatment with 4 mm/s beam speed, resulted in an occurrence of compressive residual stresses, improved fatigue resistance and reduced scatter.
- Murakami model applied to specimens with laser treatment with 4 mm/s beam speed was quite conservative, which is in a good agreement with retardation effects of compressive residual stresses to short crack growth.

Acknowledgements

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